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Critical Currents and AC Losses in Model YBCO Structures

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14. ABSTRACT

This report results from a contract tasking Institute of Electrical Engineering as follows: The contractor will investigate yttrium-barium-copper oxide (YBCO) coatings divided into filaments with various widths and separations. AC loss measurements as well as magnetization measurements will be conducted using a Hall Probe magnetometer. Experimental results will then be compared with the theoretical models and predictions by the United Kingdom research group (SPC 014028).

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Motivation of our studies

- Reduction of hysteresis loss in YBCO based AC tapes → fine filamentary structure

  - Is there a limit for the filament width, below which filament J_c degrades? (A possible limitation due to finite dimensions of grain boundaries: A. M. Campbell, AFOSR Program Review, Stanford, October 2001 [1])

  - Which is the hysteresis loss in narrow YBCO filaments?
    on $LaAlO_3$ substrate
    on Ni substrate

- Understanding of coupling current behavior in YBCO filamentary tapes

  - How an AC conductor should look like?

Layout

1. **Samples**

YBCO rings with various filament width
YBCO tapes with filamentary structure

2. **Measurements of Ic and hysteresis losses in rings at 77K**

Method
Apparatus
Results

3. **Measurements of B_z at elevated frequencies (up to 500 Hz)**

4. **Parameters affecting coupling currents and transverse resistivity**

Possible arrangement of filaments and metall layer
Boundary resistivity YBCO/metal, r_b

4. Conclusions

Samples

Ring samples YBCO on LaAlO (Microphotographs of the rings see Fig.1):

mean ring diameter	D_0 = 3 mm
width:	$2w_f$ = 300 microns
	101 microns
	51 microns
	21 microns

Ring samples YBCO on Ni

mean ring diameter	D_0 = 3 mm
width:	$2w_f$ = 300 microns
	97 microns
	50 microns
	22 microns

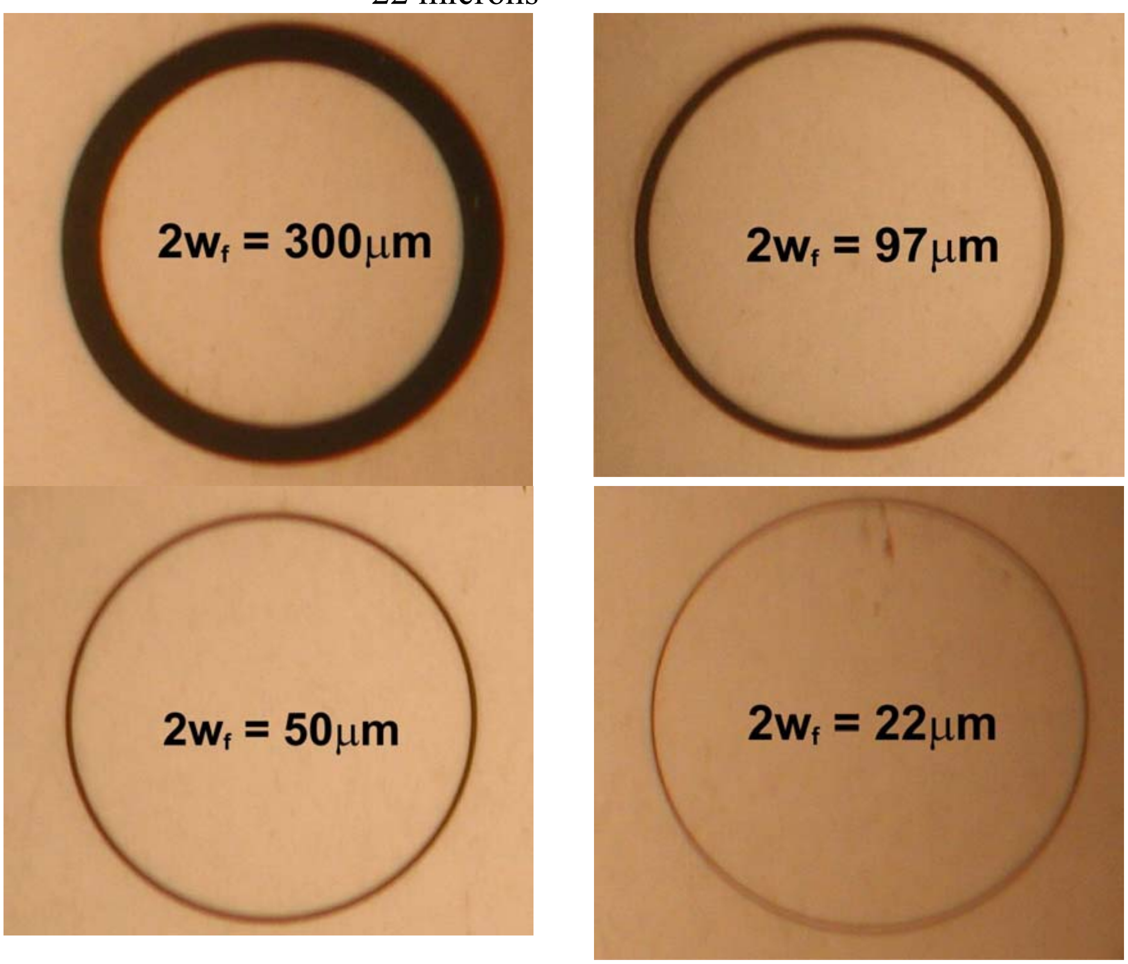


Fig. 1 YBCO rings

Untwisted filamentary tape samples (Microphotographs see Fig.2):

20 x 0.26 mm wide filaments, gap 0.04 mm (total width 6.0 mm)
40 x 0.13 mm wide filaments, gap 0.02 mm (total width 6.0 mm)
80 x 0.065 mm wide filaments, gap 0.01 mm (total width 6.0 mm)

20 x 260 µm

40 x 130 µm

80 x 65 µm

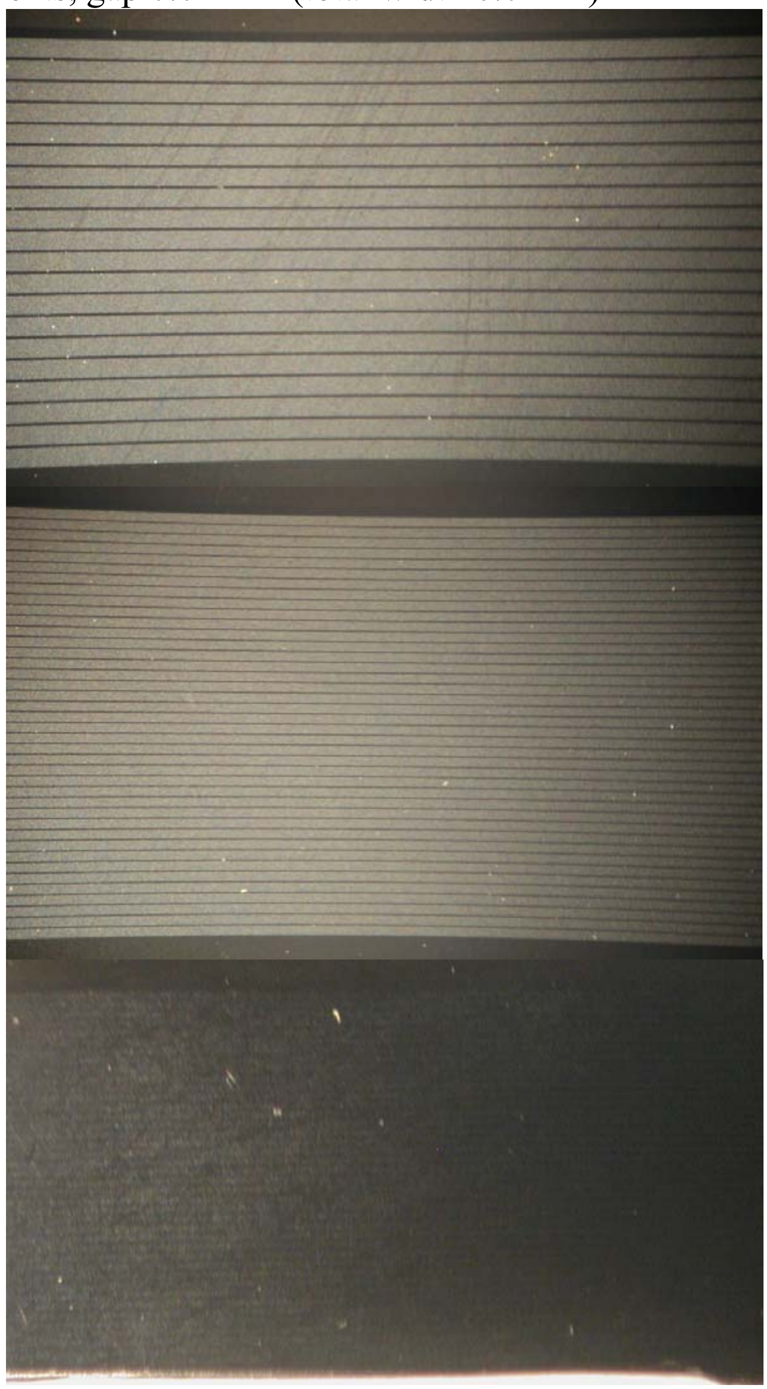


Fig. 2 YBCO filaments

Measurements of B_z vs B_e for rings, determination of E-I curves and I_c

The measuring method is described in [2].

The sample has a form of a ring with the mean ring radius R_0 (diameter D_0), the thickness d and the width of the current path $2w_f$

Measurement of current I:

→ An external magnetic field B_e induces a current I in the ring
→ this current creates magnetic field B_s,
→ B_s is measured by a Hall Probe (HP)

The value of B_s on the ring axis in the distance z from the ring is

$$B_s(r=0, z) = (\mu_0 I R_0^2/2)(R_0^2 + z^2)^{3/2} \qquad (1)$$

→ I is calculated from B_s from Eq.(1)

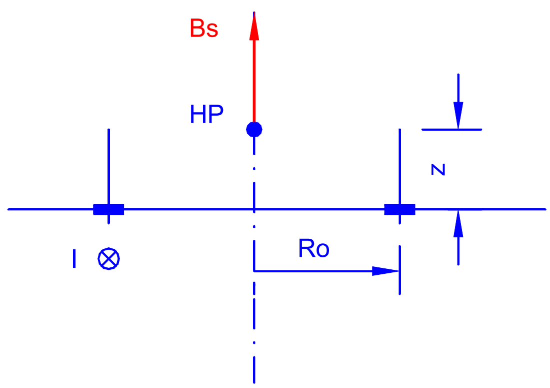


Fig. 3

Determination of E – dynamic regime

The rate of change of the external magnetic field, dB_e/dt, governs the electric field in the ring:

$$E = (R_0/2)\, dB_e/dt \qquad (2)$$

→ Measuring B_s as a function of B_e at various dB_e / dt = const. we obtain a family of hysteresis loops
→ E is determined from Eq (2)

Determination of E – static regime

In this case the electric field is governed by the decay of the induced current dI/dt

$E = (1/2\pi R_0)\, L_{ring} dI/dt$ (3)

E is in this case much smaller than E in dynamic experiments (by several orders of magnitude)

In experiments we measured I several minutes after induction of the ring current

Hysteresis losses in YBCO rings and filaments with different width

→ Hysteresis losses are determined from the hysteresis loops $M \sim B_s$ measured as a function of B_e

Loss per cycle in a ring $A_{h,ring} = \int_{-Be}^{Be} M dBe$ [J]

→ M axis calibration is based on the knowledge of I_c using Equations (there is a difference between M_{ring} and $M_{fil,1m}$):

Magnetic moment of the ring $M_{ring} = I_c\, \pi D_0^2/4$ [Am^2]

Critical current in the ring $I_c = M_{ring}\, 4/(\pi D_0^2)$

Magnetic moment of the filament per unit length

$M_{fil,1m} = I_c\, w_f/2 = M_{ring}\, 2w_f/(\pi D_0^2)$

The ratio of magnetic moments of the filament per unit length and of the ring is:

$$\mathbf{M_{fil,1m} / M_{ring} = 2w_f / (\pi D_0^2)}$$

Experimental set-up

Low frequency measurements at 77 K(from 1 mHz up to 100 mHz)

Main parts:

- Cu magnet producing external fields up to 0.4 T with f up to ~ 100 mHz, supplied by a bipolar power supply
- Hall Probe with the active area of ~ 0.05 x 0.05 mm and sensitivity of about 15μV/Gauss
- coordinate system for the Hall probe movement x, y, z

Photo (Fig. 4) shows the disassembled system for low frequency experiments.

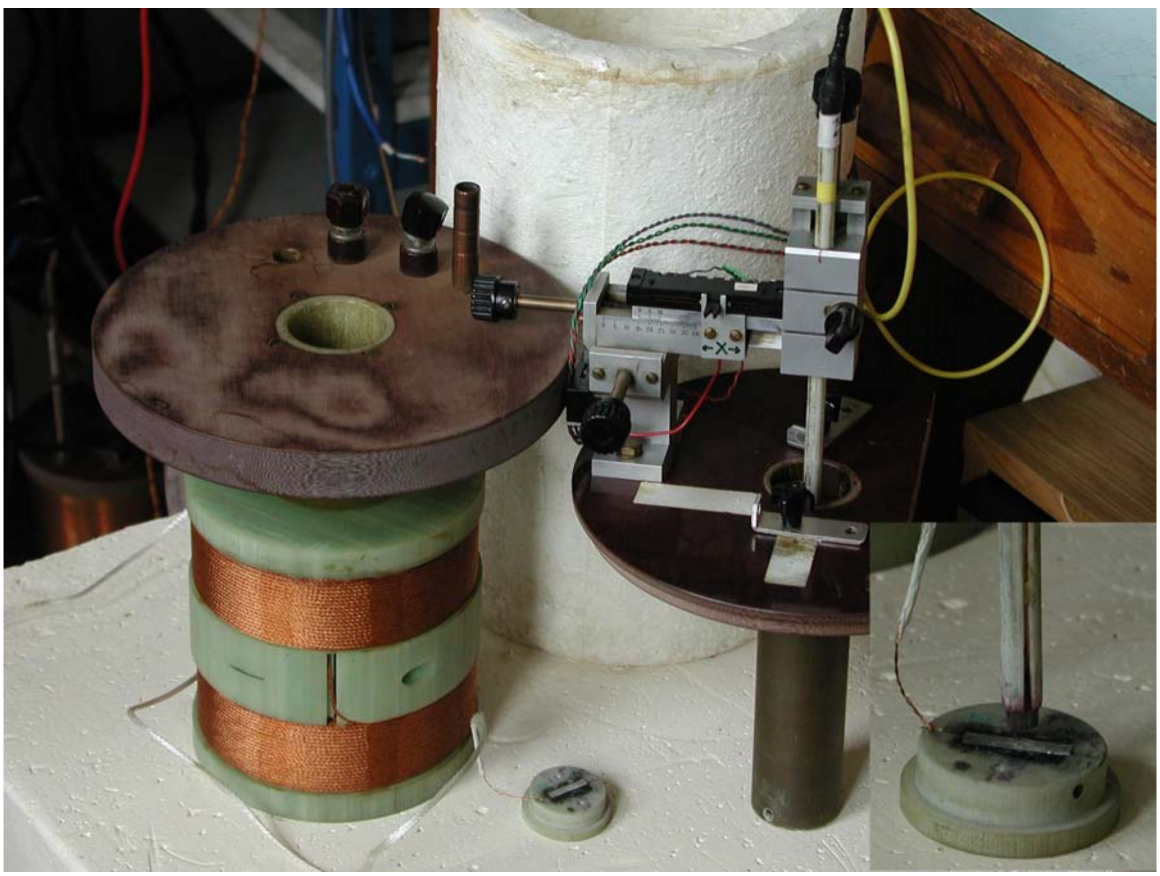


Fig. 4

Measurements at elevated frequencies at 77 K (from 1 Hz up to l kHz)

Main parts:

- Cu magnet producing B_e up to 50 mT
- wide band amplifier
- high speed voltmeter (100 000 readings/sec)
- coordinate system

Low frequency measurements at 4.2 K

Main parts:

- low hysteresis superconducting magnet producing 2T
- pick-up coils
- recording system

Measurements at elevated frequencies at 4.2 K

Measurement of longer samples

Some years ago we developed a split race track coil system wound of AC NbTi cable with working space of 20 x 20 mm and length of 180 mm. The maximum field at 50 Hz, 4.2 K was 0.25 T. This magnet is suitable for measurements of longer samples (twisted YBCO tapes).

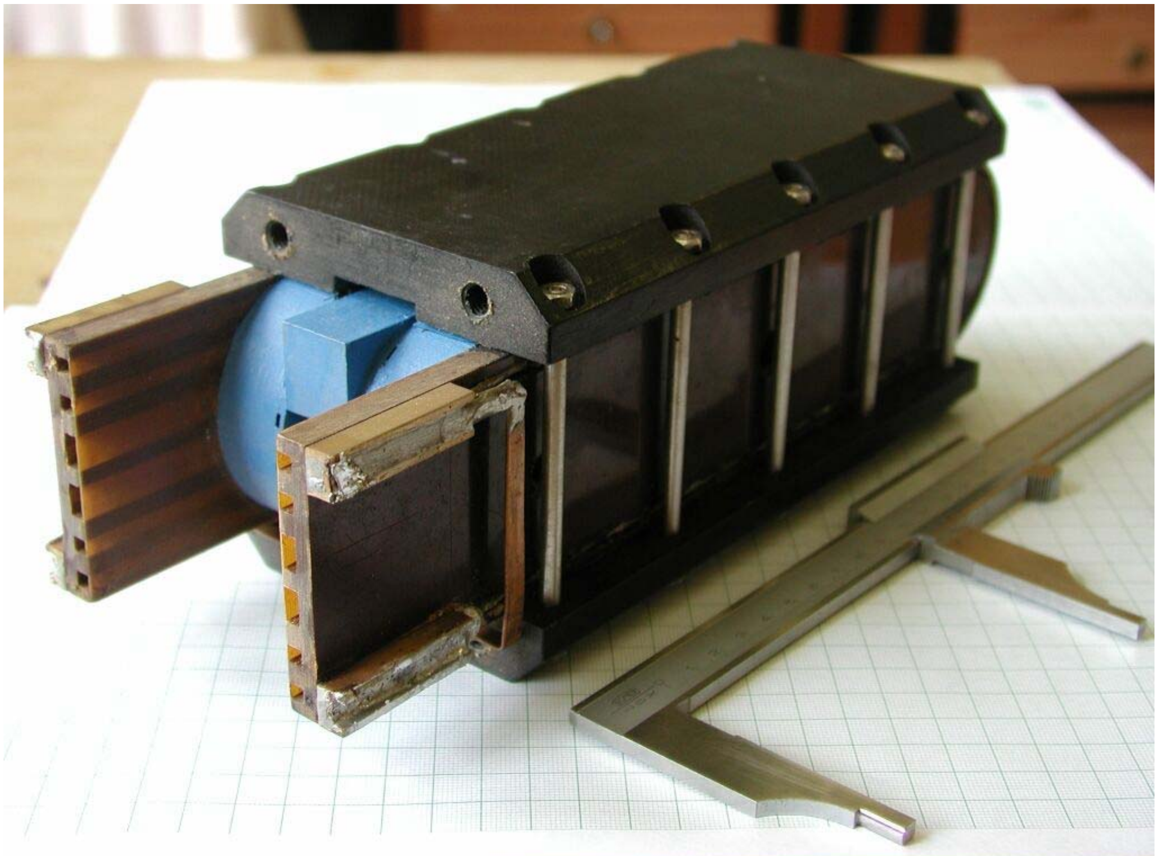
Self inductance of the coil is 1.34 mH. The inductive voltage at 400 Hz is cca 900 V. Critical current in AC mode is ~265 A.

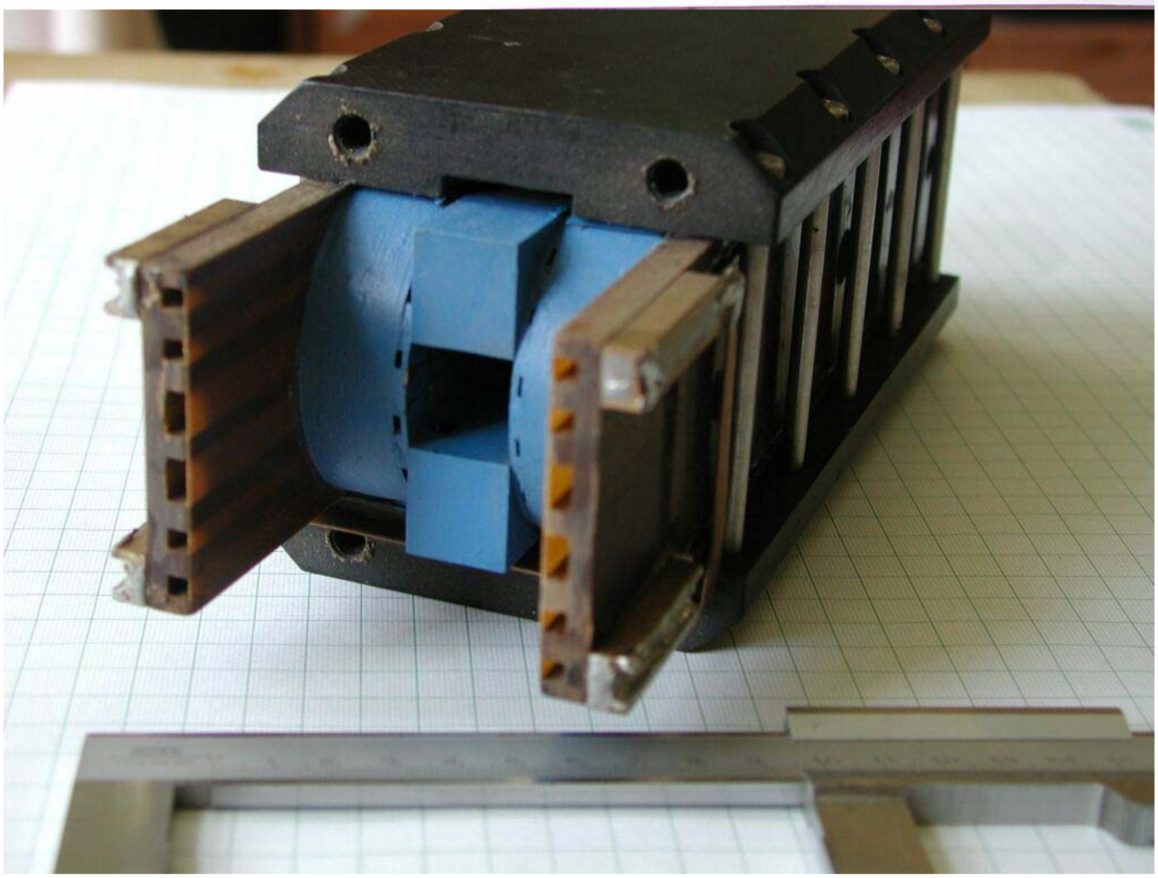
We suppose that the magnet could be modified so that a higher field could be achieved (reduction of the gap between coils, perhaps insertion of a ferromagnetic yoke).

More detailed data on the coils see:

J. Kokavec, J. Pitel, M. Majoros, M. Polak, Race track dipole magnet with working space 20 x 20 x 180 mm operating at 50 Hz up to 0.25 T, Prague, The fourth International Conference CRYOGENICS '96,Proceedings, page 13-16

The photograph of the coil is in the following Figure:





RESULTS

Hysteresis loops $B_s(B_e)$ and I-V curves in rings

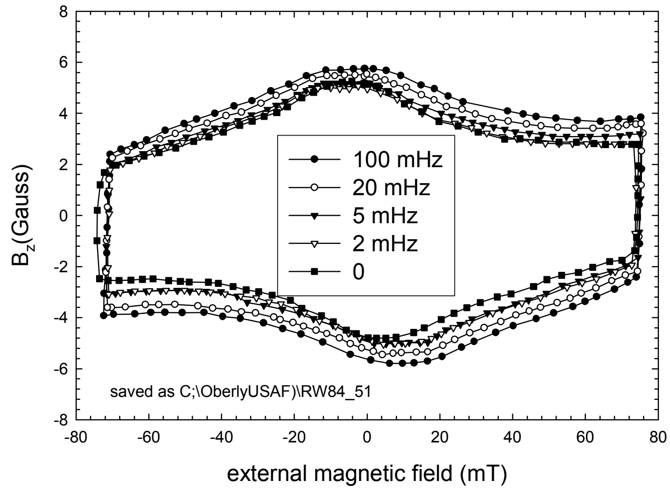


Fig. 5 Ring YBCO on LaAlO with $2w_f = 300$ microns

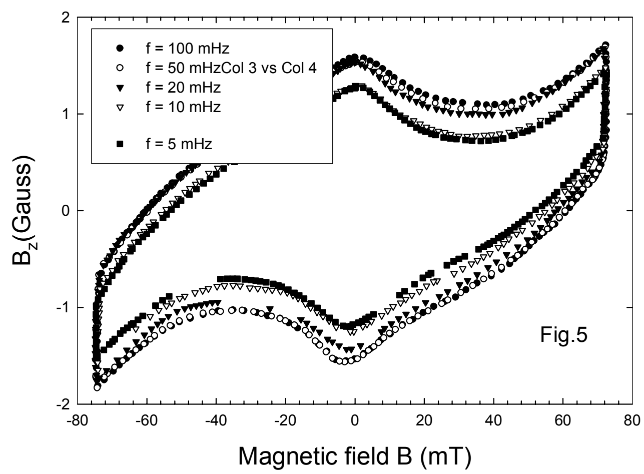


Fig. 6 Ring YBCO on LaAlO with $2w_f = 51$ microns

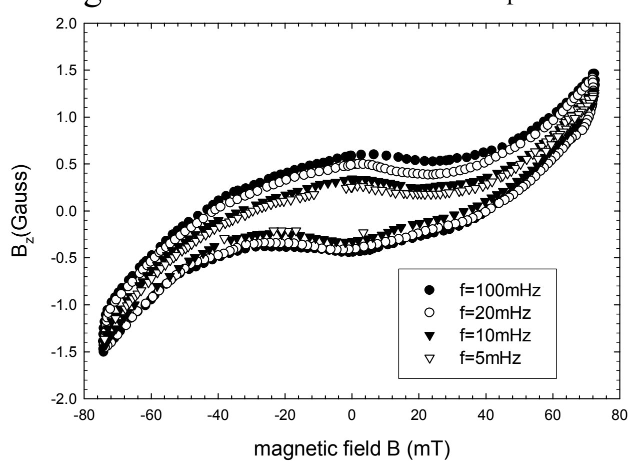


Fig. 7 Ring YBCO on LaAlO with $2w_f = 21$ microns

A comparison of hysteresis curves measured with ring havig different $2w_f$

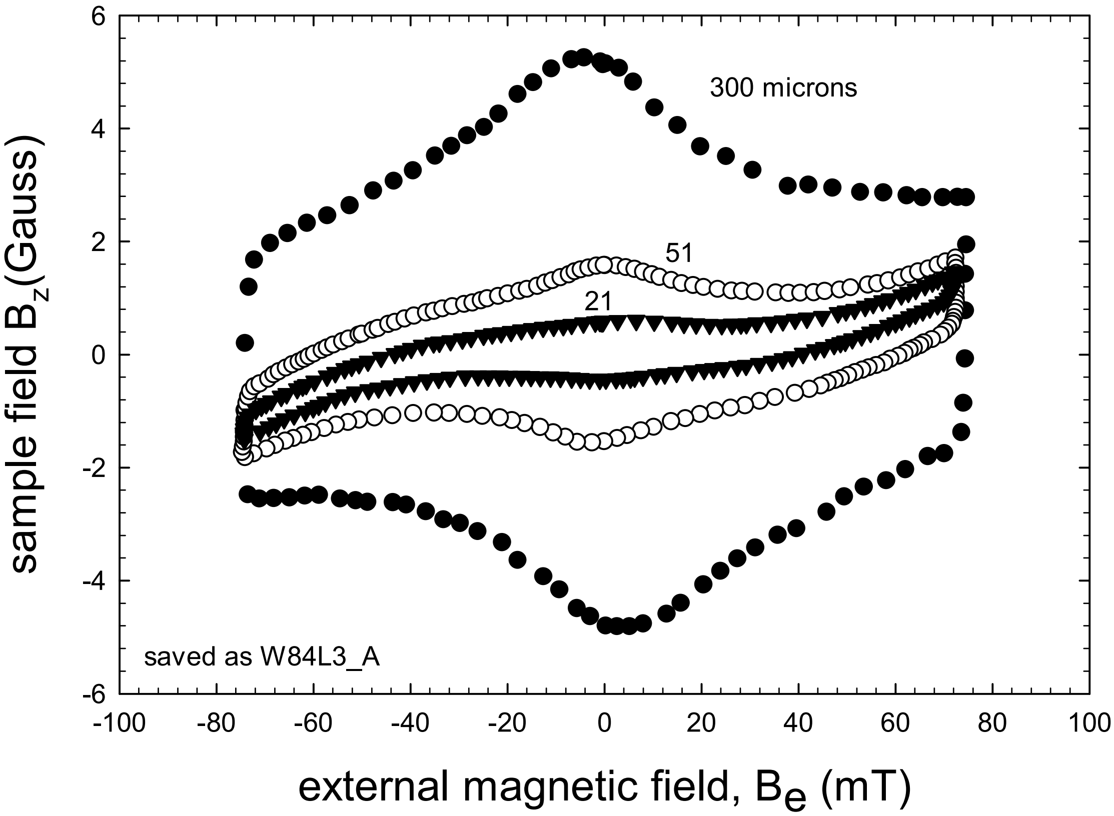


Fig. 8 Bz versus Be measured with rings 300, 51 and 21 microns at f = 100 mHz

The area of the hysteresis loop decreases with decreasing filament width

I-V curves determined from $B_z(B_e)$ measurements in rings at lower frequencies

Electric field-current curves for YBCO rings on $LaAlO_3$ with current path width 300 microns, 51 microns and 21 microns
T = 77 K, B_e=0

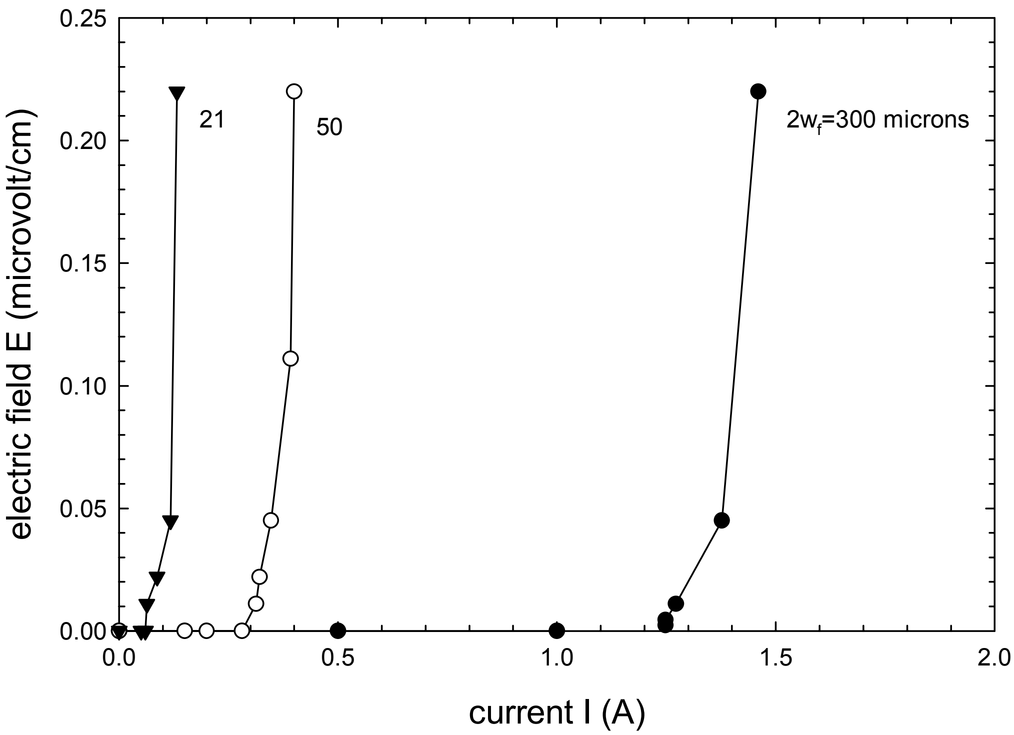


Fig. 9

Magnetic field due to magnetization currents measured in the vicinity of rings in static regime ($dB_e/dt = 0$)

SAMPLES YBCO ON LaAlO

Sample with $2w_f$ = 300 microns	**Fig. 10**
Sample with $2w_f$ = 51 microns	**Fig. 11**
Sample with $2w_f$ = 21 microns	**Fig. 12**

Magnetic field B_z at filamentary sample

Sample with $2w_f$ = 65 microns measured at elevated frequencies **Fig. 13**

SAMPLES YBCO/Ni (Rings)

Sample with $2w_f$ = 300 microns	**Fig. 14**
Sample with $2w_f$ = 300 microns + 97 microns	**Fig. 15**

Profiles $B_z(y)$ measured at various distances z from the ring plane
Ring W84L3, $2w_f$= 300 microns

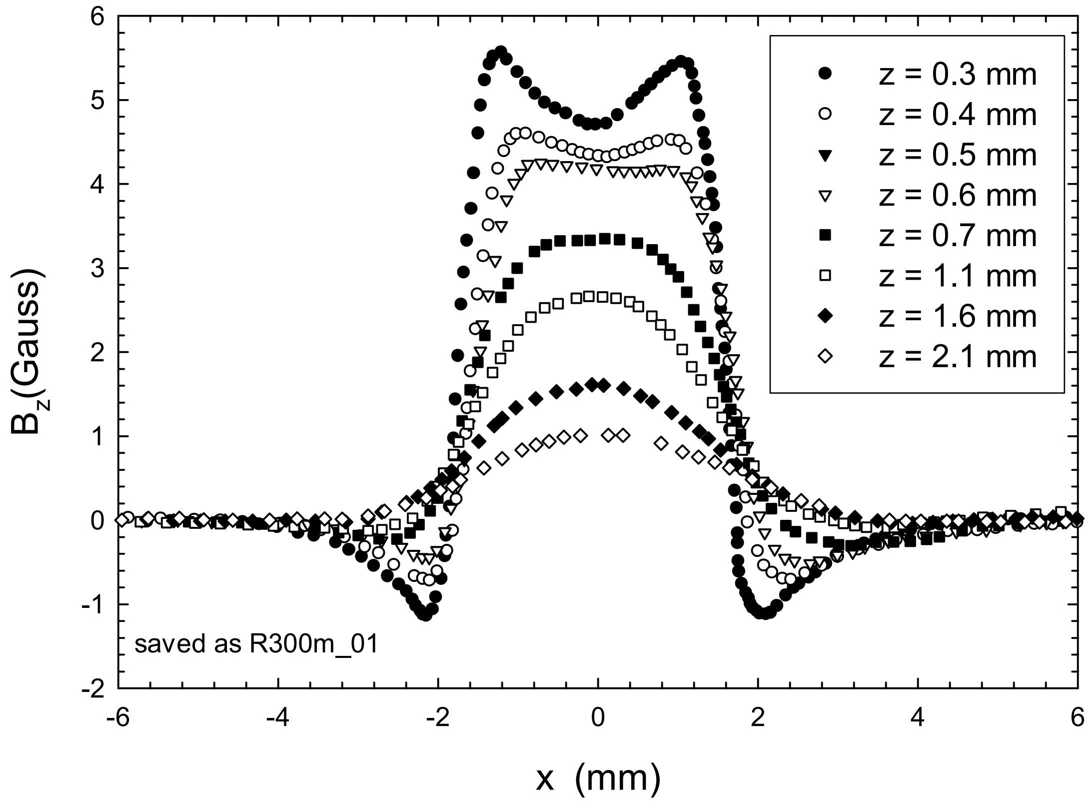
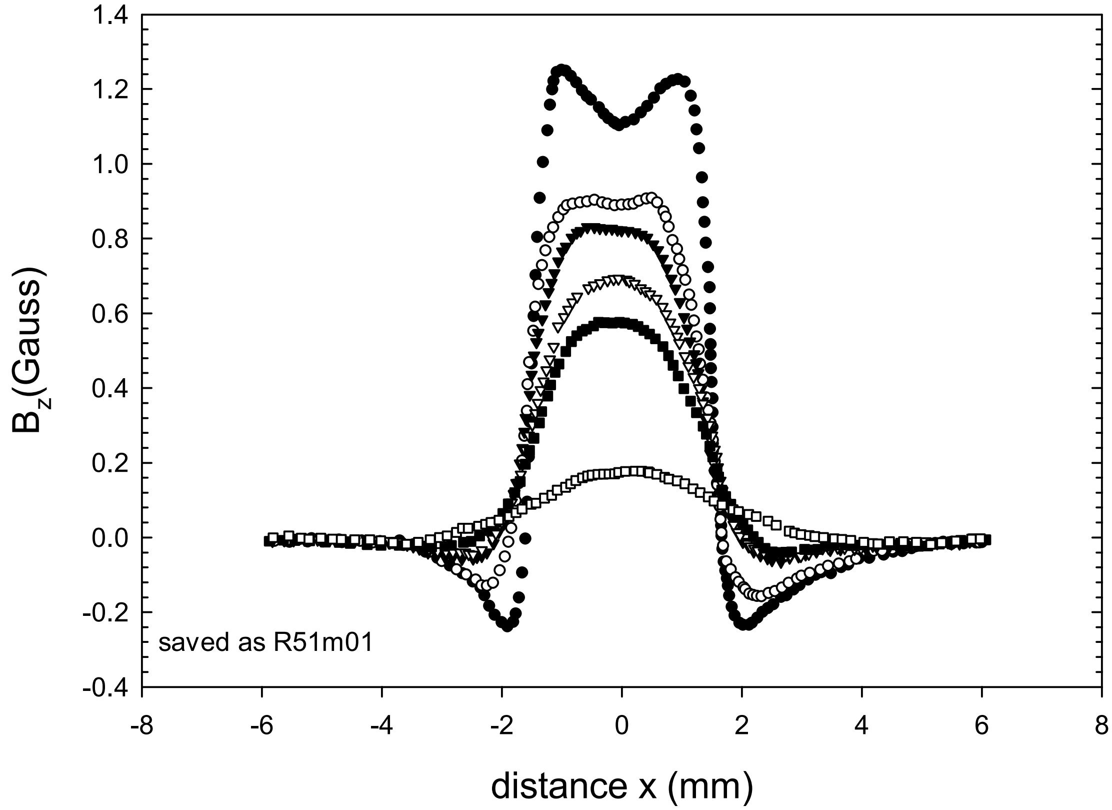


Fig. 10

Profiles $B_z(y)$ measured in various distanced z from the ring plane
Ring W84L3, $2w_f$=51 microns



Distances from the top to the bottom
z=8.8 mm
z=8.7mm
z=8.6mm
z=8.5mm
z=8.2mm
z=7.5mm

Fig. 11

W84L3

RING D_0= 3 mm, $2w_f$ = 21microns

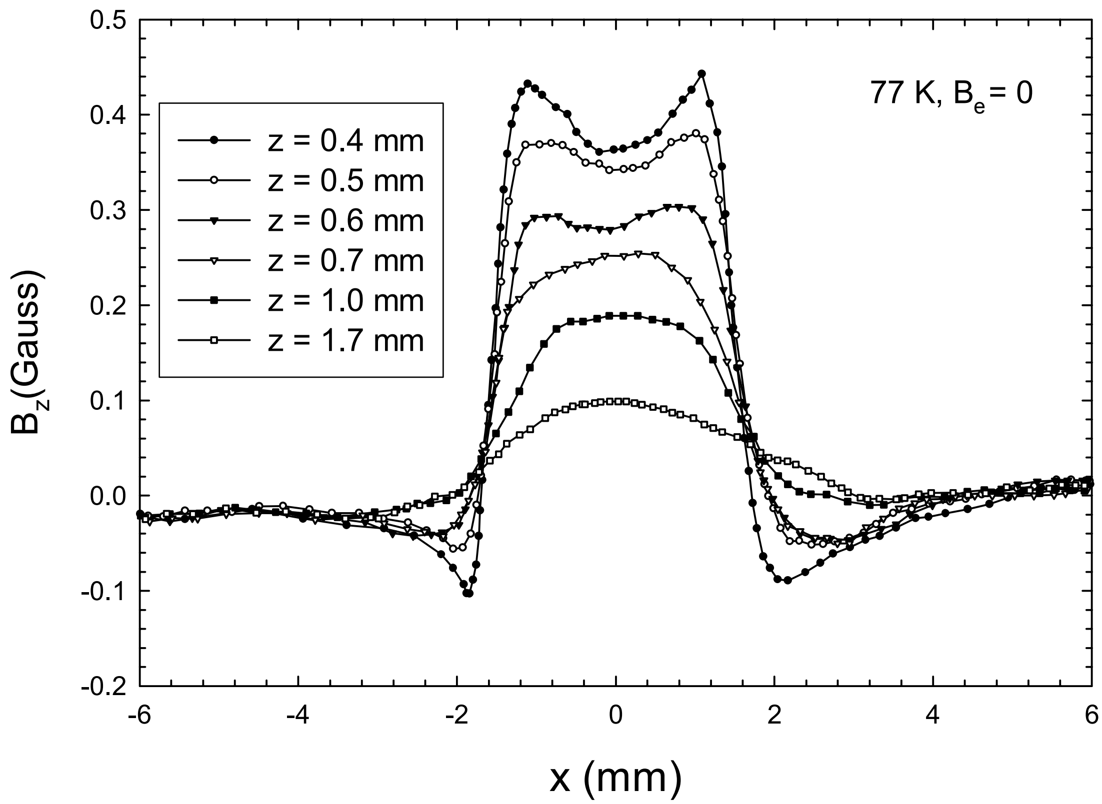


Fig. 12

YBCO on $LaAlO_3$

Critical currents and hysteresis losses in filaments determined from measurements with rings (curves $B_z = f(B_e)$

	$2w_f = 300\mu m$	**$2w_f = 51\mu m$**	**$2w_f = 21\mu m$**
$I_c(0.22\mu V/cm, B_e=0)$ [A]	1.46	0.4	0.132
$I_{c1}(0.22\mu V/cm, B_e=0)$ [A/m]	$4.87\ 10^{3}$	$7.84\ 10^{3}$	$6.28\ 10^{3}$
$M(B_e = 0)$ [Am^2]	$1.03\ 10^{-5}$	$2.83\ 10^{-6}$	$9.32\ 10^{-7}$
$A_{h,ring}$ [J/cycle]	$2.02\ 10^{-6}$	$4.89\ 10^{-7}$	$1.82\ 10^{-7}$
$W_{h,ring}(50\ Hz)$ [W]	$1.01\ 10^{-4}$	$2.45\ 10^{-5}$	$9.10\ 10^{-6}$
$W_{h,ring}(400\ Hz)$ [W]	**$8.08\ 10^{-4}$**	**$1.96\ 10^{-4}$**	**$7.28\ 10^{-5}$**
$2w_f/(\pi D_0)^2$	10.6	1.8	0.7427
$W_{h,fil}(1m, 50\ Hz)$ [W]	$1.07\ 10^{-3}$	$4.41\ 10^{-5}$	$6.7\ 10^{-6}$
$W_{h,fil}(1m, 400\ Hz)$ [W]	**$8.56\ 10^{-3}$**	**$3.53\ 10^{-4}$**	**$5.36\ 10^{-5}$**

FILAMENTARY SAMPLE, $2w_f$ = 65 microns

Magnetic fields due to magnetization currents measured at elevated frequencies (up to 100 Hz)

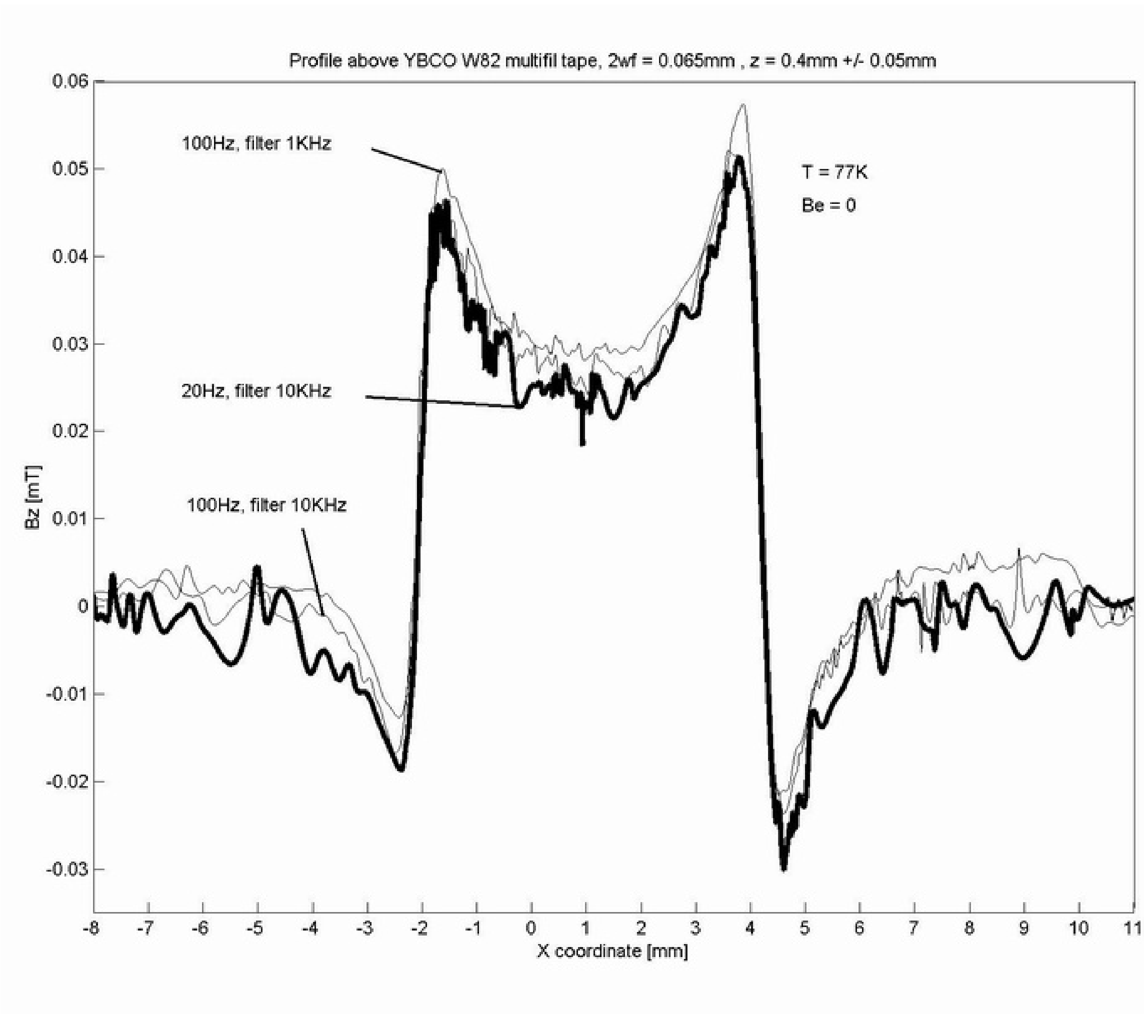


Fig. 13

Magnetic field close to YBCO rings on Ni substrate

Main problem:

a strong contribution of Ni to the measured field and AC losses

↓

in rings with narrow filaments the signal from the superconductor is << signal from Ni

Profiles B_z measured with rings with $2w_f = 300$ and 97 microns – a comparison:

B_z measured in the vicinity of YBCO rings with $2w_f$= 300 microns and 97 microns.
The rings are placed on common Ni substrate 10 x 20 mm

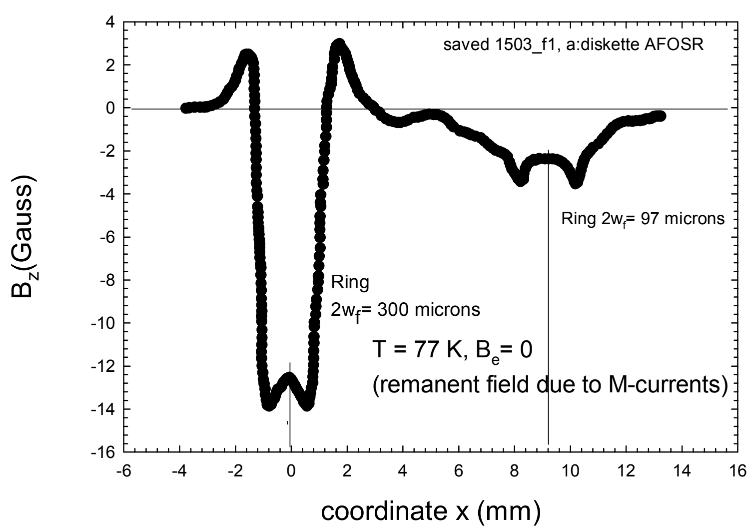


Fig. 14

B_z vs x for YBCO ring on Ni with $2w_f$ = 300 microns

T=77 K, B_e = 0,measured at various distances z

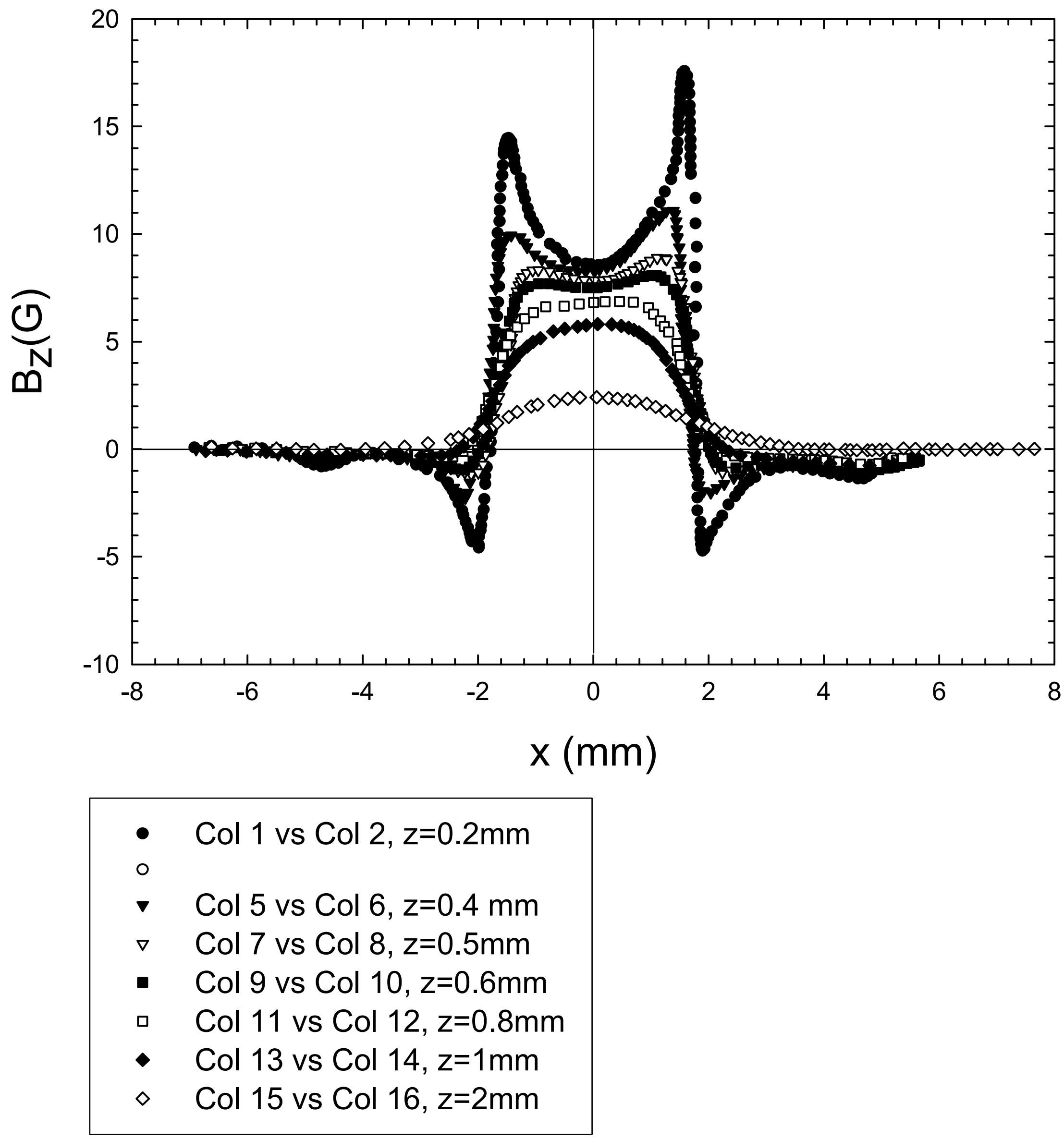


Fig. 15

EXPERIMENTS AT 4.2 K

Set-up: **low hysteresis AC coil (operating at 50 Hz up to 2 T)**
pick-up coils with cca 5000 turns
analog integrator

Measured samples:

sample with $2w_f$ = 130 microns
sample with $2w_f$ = 65 microns

Magnetization of filamentary tape sample with $2w_f$=130 microns.
No influence of frequency observed up to ~50 mHz

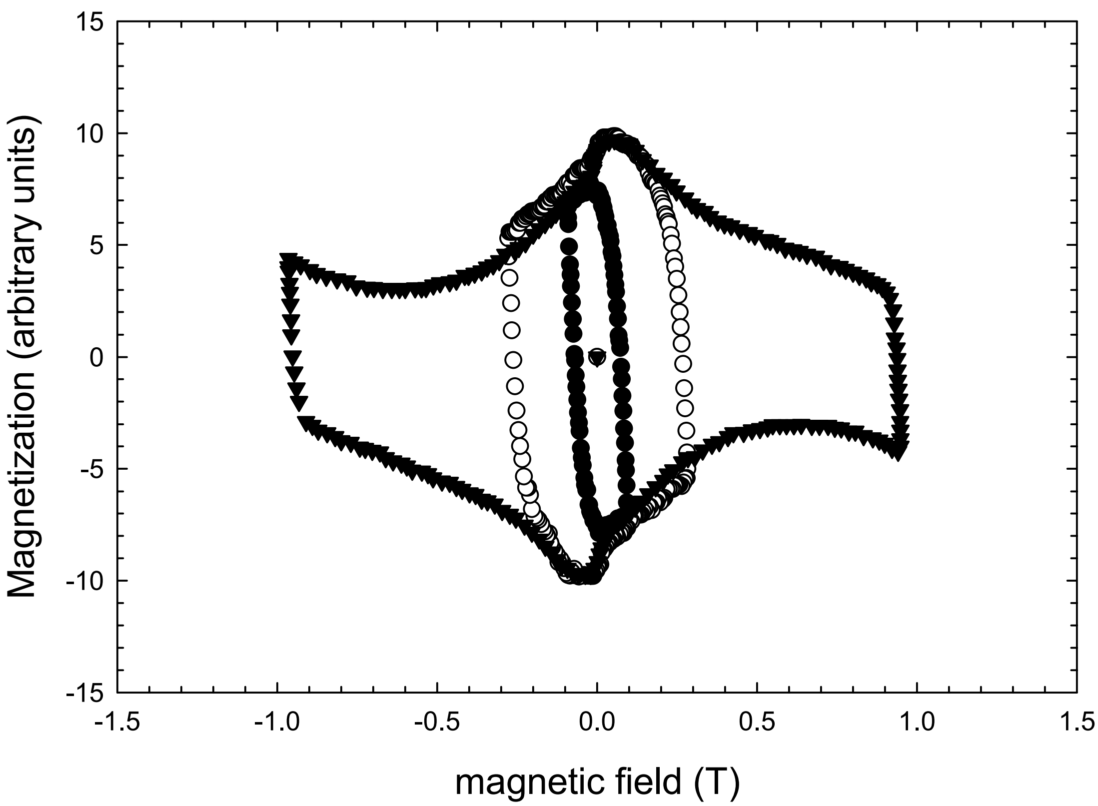


Fig. 16

Understanding of coupling current behavior in filamentary YBCO coated conductors

Parameters affecting coupling current behavior

a. Architecture of the coated conductor

b. Properties of the stabilization metal (Ag, Au)
(problems with thicker layers)

c. Resistivity of the boundary YBCO/stabilization
(good layers have resistivities better than $10^{-6}\,\Omega cm^2$)

d. Properties of the boundary YBCO/buffer layer/substrate (Ni or Ni with additives)
(*actually coated conductors use insulation buffer layer)*

Parameters affecting effective transverse resistivity, ρ_{eff}

The paths of coupling currents are shown in the following Figure:

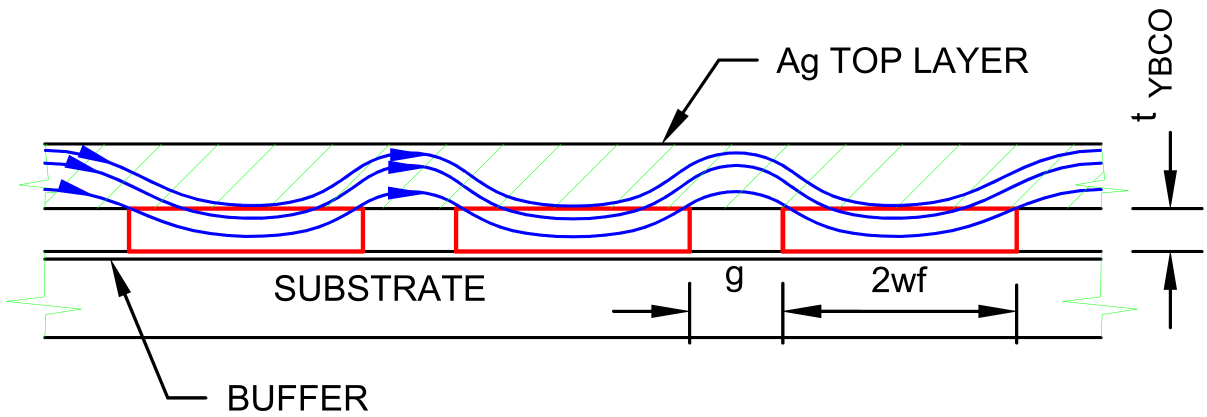


Fig. 17

R_1	resistance of the top Ag layer per unit length [Ω/m]
ρ_b	boundary resistivity YBCO/Ag [Ωm^2]
$2w_f$	filament width
g	gap between neighboring filaments

An estimate of the boundary resistivity, ρ_b, for a model filamentary tape with the following parameters:

20 filaments with $2w_f = 0.26$ mm, filament thickness 0.25 microns, g = 0.04 mm, tape width 2w = 20 x 0.3 mm = 6 mm, tape length L = 1 cm, $\rho_b = 10^{-6}$ Ωcm^2 (typical value for a "good" layer), t_{Ag}=1 μm, T = 77 K, $\rho_{Ag}(77) = 2.5 \times 10^{-7}$ Ωcm for bulk samples (see, for example, [4]: Y. Iwasa,et al., Cryogenics 1993 Vol 33 No 8, p. 836)
The silver resistance of 20 gaps with g=0.04 mm is

$$\mathbf{R_{20gaps} = 20\ \rho_{Ag}\ g\ /2w = 20\ 2.5\ 10^{-7}\ \Omega cm\ 0.004\ cm/(1\ cm\ 10^{-4} cm) = 2 \times 10^{-4}\ \Omega}$$

Resistance of the boundary filament/Ag per 1 filament

$$\mathbf{R_b = \rho_b/(L \times 2w_f) = 10^{-6}\ \Omega cm^2/\ (1 cm \times 0.026\ cm) = 3.85\ 10^{-5}\ \Omega}$$

20 filaments in series have the boundary resistance 20 x higher, $R_{b(20fil)}$=7.7 10^{-4} Ω.

The total resistance of the filamentary conductor is

$$\mathbf{R_t = R_{20gaps} + R_{b(20fil)} = 2 \times 10^{-4} + 7.7\ 10^{-4}\ \Omega = 9.7\ 10^{-4}\ \Omega}$$

and the effective resistivity in the conductor thickness formed by silver and YBCO (1 micron Ag+ 0.25 micron YBCO)

$$\mathbf{\rho_{eff} = R_t\ (1cm \times 1.25\ 10^{-4})/0.6\ cm \sim 2\ 10^{-7}\Omega cm}$$

From this example it is seen that increasing the Ag thickness one reduces the transverse resistivity, but this reduction is strongly affected by the transverse resistivity.

Conclusions

1. The reduction of the filament width from 300 microns down to 21 microns did not reduce the critical current I_{c1} in YBCO thin films deposited on $LaAlO_3$ substrates

Filament width	I_{c1m} (0.22 μV/cm)
300 microns	4870 A
51 microns	7840 A
21microns	6280 A

2. Due to strong contribution of Ni to the sample magnetic field the method to determine I_c in ring samples is applicable for wider filaments only

3. The measured hysteresis losses per 1m long filaments, measured at 100 mHz frequency, triangular field waves, and are the following

300 microns	8.56 mW at 400 Hz
51 microns	0.353 mW at 400 Hz
21microns	0.0536 mW at 400 Hz

Measurements of B_z (x=0) vs frequency for frequencies up to 200 Hz showed only a very little increase of B_z. We believe that hysteresis losses in thin YBCO filaments have a small frequency dependence.

References

[1] A. M. Campbell, AFOSR Program Review, Stanford, October 2001

[2] M. Polak, V. Windte, W. Schauer, J. Reiner, A. Gurevich, H. Wuhl, Contactless measurement of voltage-current characteristics of high-T_c thin film superconductors, Physica C 174 (1991) 14-22

[3] M. Polak, W. Zhang, J. Parrell, X. Y. Cai, A. Polyanskii, E. E. Hellstrom, D. C. Larbalestier, M. Majoros, Current transfer length and the origin of linear components in the voltage - current curves of Ag-sheathed BSCCO composites, Supercond. Sci. Technol. 10 (1997) 769-777

[4] Y. Iwasa,et al., Cryogenics 1993 Vol 33 No 8, p. 836